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SUBSTRATE OPTIMIZATION FOR INTEGRATED CIRCUIT ANTENNAS

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Abstract Imaging systems in microwaves, millimeter and submillimeter wave applications employ printed circuit antenna elements. The effect of substrate properties is analyzed in this paper by both reciprocity theorem as well as integral equation approach for infinitesimally short as well as finite length dipole and slot elements. Radiation efficiency and substrate surface wave guidance is studied for practical substrate materials as GaAs, Silicon, Quartz and Duroid.

Summary

This paper provides a comprehensive analysis of various materials as substrates for printed circuit antennas. Such antennas find increasing use as single antenna elements, in phased and imaging arrays in microwaves [1] - [3] as well as in the millimeter and submillimeter frequency range [4] - [9]. In order to optimize the performance of a dipole or slot antenna integrated into a system supported by a substrate, the effect of substrate parameters such as its thickness b and relative dielectric constant ε_r on antenna input impedance, antenna resonant length, radiation pattern, radiation efficiency and bandwidth must be analyzed. Radiation efficiency is defined as the ratio of radiated power to power coupled into TM and TE substrate surface wave modes. By considering the theory of surface wave modes in dielectric slabs [10], [11] or integrated dielectric waveguides [12] and the reciprocity theorem, the power radiated by infinitesimally small slots and dipoles into a substrate and into air has been computed. An elementary slot is considered to radiate into a substrate of thickness b on one side of the ground plane on which it has been cut and into vacuum on the other side. The power coupled into surface modes has been found as

$$P = \begin{cases} \dfrac{3\varepsilon_r \lambda}{16h_e} & \text{for TM modes} \\[2ex] \dfrac{3\varepsilon_r \lambda_o \cos^2\theta}{16h_e} & \text{for TE modes} \end{cases} \qquad (1)$$

where P is normalized to the power the slot would radiate in vacuum, θ is the angle of incidence within the substrate and h_e is the dielectric waveguide effective height as defined in [12], for an elementary dipole printed on a substrate of thickness b (without ground plane) the corresponding power coupled into surface modes is

$$P = \begin{cases} \dfrac{3\lambda_o \cos^2\phi}{4h_e} & \text{for TE modes} \\[2ex] \dfrac{3\lambda_o \sin^2\phi \cos^2\theta}{4h_e} & \text{for TM modes} \end{cases} \qquad (2)$$

where ϕ is the phase shift of the wave at the interface [12]. Figure 1 shows the calculated power distribution for a dielectric constant of 12 (appropriate for silicon and gallium arsenide substrates).

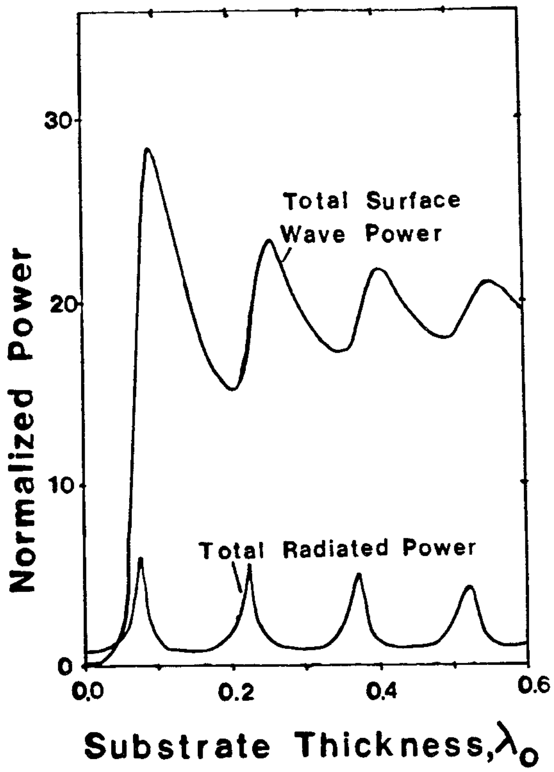

Figure 1a

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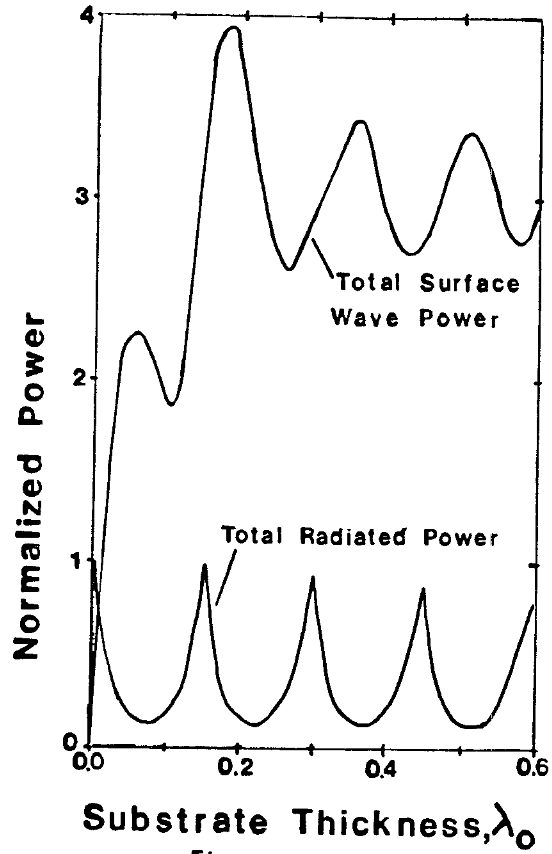


Figure 1b

It is clear that unless the substrate is quite thin, most of the power is lost to surface wave modes. Figure 2 shows how these surface wave losses affect the gain.

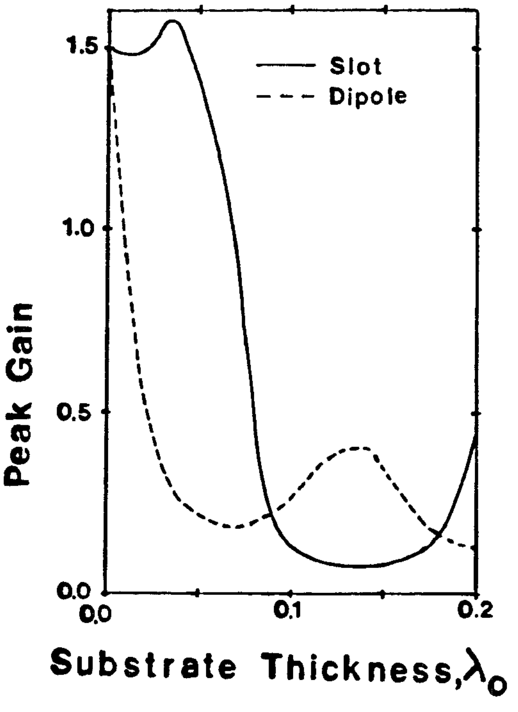


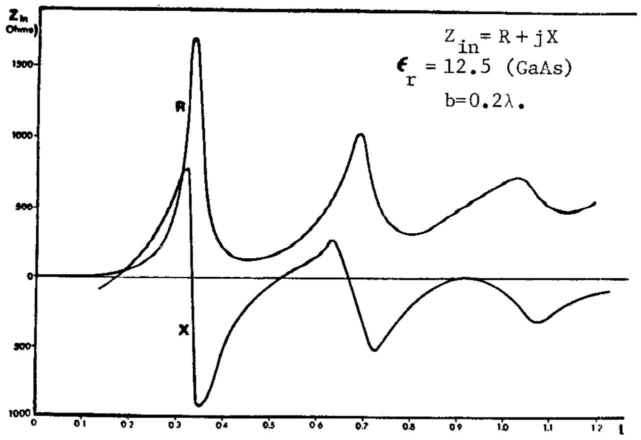
Figure 2

The dipole gain is reduced even for very thin substrates. The slot gain is also reduced when the substrate is thicker than $\lambda_0/20$. The required thickness at 600 GHz is only 25 μm. This will make the fabrication difficult and curving the back of the substrate to form a lens would be preferable [8].

Printed antennas are finite in length and integral equation techniques are needed to obtain with precision their properties as e.g. the effect of substrate thickness and permittivity on antenna input impedance, radiation pattern, bandwidth, etc. To this end the Pocklington type integral equation [13] - [15]

$$\bar{E}(\bar{r}) = \int_0^L [k_0^2 \bar{\bar{I}} + \nabla\nabla] \cdot \bar{\bar{G}}(\bar{r}/\bar{r}') \cdot \bar{J}(\bar{r}')dx' \quad (3)$$

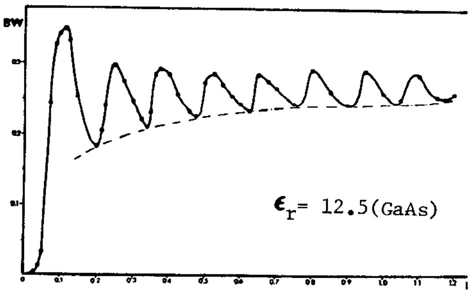
where $\bar{\bar{I}}$ is the unit dyadic, $\bar{J}(\bar{r}')$ the unknown current distribution and $\bar{\bar{G}}$ the dyadic Green's function pertinent to the geometry of the problem is solved numerically by employing the method of moments [16]. As an example for this paper the input impedance versus antenna length is shown in Figure 3 for a dipole printed on a GaAs substrate of thickness $b = 0.2\lambda_0$, backed by a ground plane.



Input Impedance Zin vs. Dipole-Length L

Figure 3

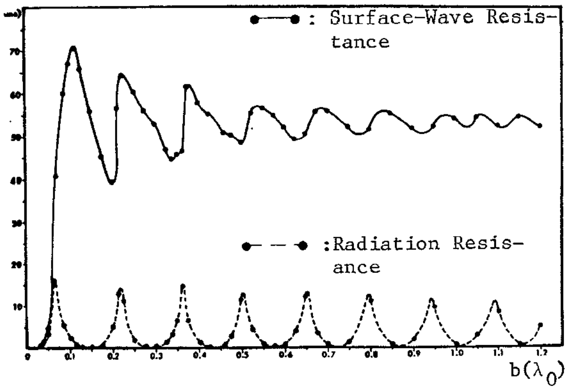
Figure 4 shows the variation of antenna bandwidth vs. substrate thickness.



Bandwidth BW vs. Substrate Thickness b

Figure 4

The surface wave and radiation resistance are shown in Figure 5 wherefrom it is concluded that most of the power is coupled into surface wave modes and therefore GaAs is not an effective substrate for microstrip antennas.



Surface-Wave Resistance and Radiation Resistance vs. Substrate Thickness b for $_r = 12.5$ and Resonant Length of the Dipole

Figure 5

Extensive data on the optimization of printed circuit antennas on quartz, silicon, gallium arsenide and duroid will be given in addition to the results presented herein.

Conclusion

Effective techniques are presented to optimize printed circuit antennas as well as slot elements integrated into a system supported by a substrate. The effect of substrate thickness and permittivity on antenna properties is analyzed thoroughly for typically used substrates.

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